(54) Title: OPTIMIZATION OF RESERVOIR, WELL AND SURFACE NETWORK SYSTEMS
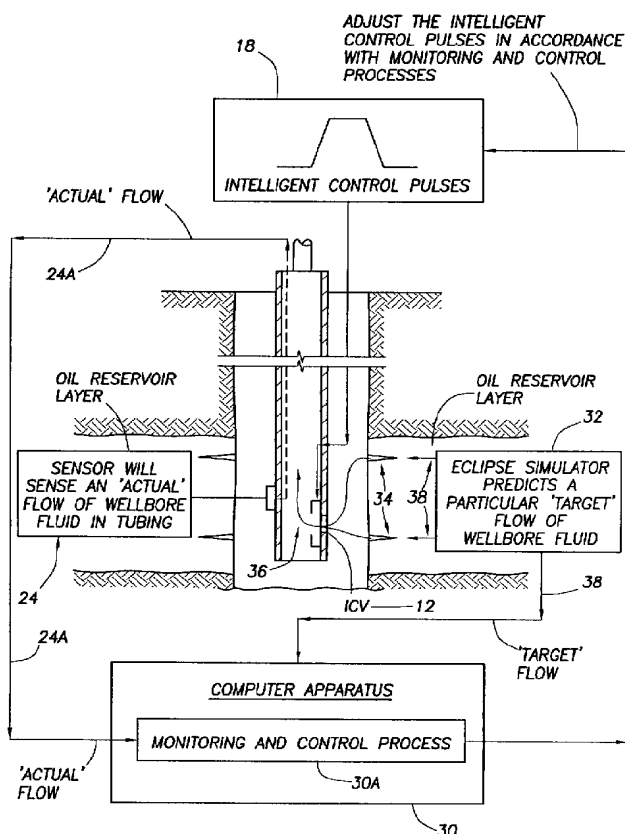
(57) Abstract: A method and associated apparatus continuously optimizes reservoir, well and surface network systems by using monitoring data and downhole control devices to continuously change the position of a downhole intelligent control valve (ICV) (12) until a set of characteristics associated with the "actual" monitored data is approximately equal to, or is not significantly different than, a set of characteristics associated with "target" data that is provided by a reservoir simulator (32). A control pulse (18) having a predetermined signature is transmitted downhole thereby changing a position of the ICV. In response, a sensor (14) generates signals representing "actual" monitoring data. A simulator (32) which models a reservoir layer provides "target" data. A computer apparatus (30) receives the "actual" data and the "target" data and, when the "actual" data is not approximately equal to the "target" data, the computer apparatus (30) executes a "monitoring and control process" program code which changes the predetermined signature of the control pulse to a second and different predetermined signature. A new pulse having the second predetermined signature is transmitted downhole and the above process repeats until the "actual" data received by the computer apparatus (30) is approximately equal to the "target" data.

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

The TItle is too long. See PCT Rule 4.3. The New Title is: "OPTIMIZATION OF RESERVOIR, WELL AND SURFACE NETWORK SYSTEMS".

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10   BACKGROUND OF THE INVENTION

The subject matter of the present invention relates to a process, which can be implemented and practiced in a computer apparatus, for transforming monitoring data, which can include real time or non-real time monitoring data, into decisions related to

15   optimizing an oil and/or gas reservoir, usually by opening or closing downhole intelligent control values.

In the oil and gas industry, intelligent control valves are installed downhole in wellbores in order to control the rate of fluid flow into or out of individual reservoir units.

20   Downhole intelligent control valves (ICVs) are described in, for example, the Algeroy reference which is identified as reference (1) below. Various types of monitoring measurement equipment are also frequently installed downhole in wellbores, such as pressure gauges and multiphase flowmeters; refer to the Baker reference and the Beamer reference which are identified, respectively, as references (2) and (3) below. This

25   specification discloses a process for transforming monitoring data (either real-time or non-real-time monitoring data) into decisions related to optimizing an oil or gas reservoir, usually by opening or closing a set of downhole intelligent control valves (ICV) in the oil or gas reservoir.

SUMMARY OF THE INVENTION

Accordingly, a novel 'monitoring and control' process is practiced in a monitoring and
control apparatus that is located both uphole in a computer apparatus that is situated at the
surface of a wellbore and downhole in a computer apparatus situated inside the wellbore.
That portion of the monitoring and control apparatus that is situated uphole (hereinafter,
the 'uphole portion of the monitoring and control apparatus') is responsive to a plurality
of monitoring data, where the monitoring data is received from that portion of the
monitoring and control apparatus that is situated downhole (hereinafter, the 'downhole
portion of the monitoring and control apparatus'). The 'downhole portion of the
monitoring and control apparatus' is actually comprised of a 'well testing system' that is
situated downhole in a wellbore. The 'uphole portion of the monitoring and control
apparatus' functions to selectively change a position of an intelligent control valve that is
disposed within the 'downhole portion of the monitoring and control apparatus', the
position of the intelligent control valve in the downhole apparatus being changed between
an open and a closed position in order to maintain an 'actual' cumulative volume of water
that is produced from a reservoir layer in the wellbore (or injected into a reservoir layer)
to be approximately equal to a 'target' cumulative volume of water (i.e., the 'target
value') which is desired to be produced from the reservoir layer in the wellbore (or
injected into the reservoir layer).

A simulation program, embodied in a separate workstation computer, models the
reservoir layer and predicts the 'target' cumulative volume of water (or reservoir fluid)
that will be produced from the reservoir layer (or will be injected into the reservoir layer).
The open and closed position of the Intelligent Control Valve (ICV) in the 'downhole
portion of the monitoring and control apparatus' must be changed in a particular manner
and in a particular way and at a particular rate in order to ensure that the 'actual'
cumulative volume of water (or other reservoir fluid) that is produced from the reservoir
layer (or is injected into the reservoir layer) is approximately equal to the 'target'

2

cumulative volume of water (or other reservoir fluid) that is predicted to be produced from the reservoir layer (or is predicted to be injected into the reservoir layer). It is the function of the 'uphole portion of the monitoring and control apparatus' to change the open and closed position of the ICV of the downhole apparatus in the particular manner

5 and in the particular way and at the particular rate in order to ensure that the 'actual' cumulative volume of water (or other reservoir fluid) which is produced from the reservoir layer (or is injected into the reservoir layer) is approximately equal to the 'target' cumulative volume of water (or other reservoir fluid) that is predicted to be produced from the reservoir layer (or is predicted to be injected into the reservoir layer).

10 If the position of the ICV of the downhole apparatus cannot be changed by the uphole apparatus in the particular manner and the particular way and at the particular rate in order to ensure that the 'actual' cumulative volume of water or fluid is approximately equal to the 'target' cumulative volume of water or fluid, then, the value of the 'target' cumulative volume of water or fluid that is predicted by the simulation program, which is

15 embodied in the separate workstation computer, must be changed (hereinafter, the 'changed target' cumulative volume of water or fluid). Then, once this change of the 'target' value has taken place, the above identified process is repeated; however, now, the 'target' cumulative volume of water or fluid is equal to the 'changed target' cumulative volume of water or fluid.

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Further scope of applicability of the present invention will become apparent from the detailed description presented hereinafter. It should be understood, however, that the detailed description and the specific examples, while representing a preferred embodiment of the present invention, are given by way of illustration only, since various

25 changes and modifications within the spirit and scope of the invention will become obvious to one skilled in the art from a reading of the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

A full understanding of the present invention will be obtained from the detailed

5   description of the preferred embodiment presented hereinbelow, and the accompanying

drawings, which are given by way of illustration only and are not intended to be limitative

of the present invention, and wherein:

figures 1 through 11 illustrate curves depicting cumulate zonal injection versus time (in

10   weeks);

figure 12 illustrates the monitoring and control process in accordance with the present

invention;

15 · figure 13 illustrates the slow predictive model portion of the monitoring and control

process of figure 12;

figure 14 illustrates the fast production model portion of the monitoring and control

process of figure 12;

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figures 15 through 17 illustrate an example of an intelligent control value (ICV) that can

be disposed in a well testing system that is adapted to be disposed downhole in a

wellbore; and

25   figures 18 and 19 illustrate a system including the monitoring and control process of the ·

present invention adapted for changing the position of an intelligent control valve (ICV)

in response to output signals received from one or more monitoring sensors and an

execution of the monitoring and control process of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

5   Referring initially to figures 15 through 19, an example of a system including an intelligent control valve (ICV) disposed within a well testing system adapted to be disposed downhole in a wellbore is illustrated.

In figure 15, a well testing system 10 is illustrated. The well testing system 10 of figure 15 is discussed in U.S. Patents 4,796,699; 4,915,168; 4,896,722; and 4,856,595 to

10   Upchurch, the disclosures of which are incorporated by reference into this specification. The well testing system 10 includes an intelligent control valve (ICV) 12 that is operated in response to a plurality of intelligent control pulses 18 that are transmitted downhole from the surface.

15   In figure 16, the plurality of control pulses 18 are illustrated in figure 16. Each pulse 18 or pair of pulses 18 have a unique 'signature' where the 'signature' consists of a predetermined pulse-width and/or a predetermined amplitude and/or a predetermined rise time that can be adjusted/changed thereby changing the 'signature' in order to operate the intelligent control valve 12 of figure 15.

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In figure 17, the intelligent control valve 12 of figure 15 includes a command sensor 14 adapted for receiving the control pulses 18 of figure 16, and a command receiver board 16 receives the output from the command sensor 14 and generates signals which are readable by a controller board 20.   The controller board 20 includes at least one microprocessor.

25   That microprocessor stores a program code therein which can be executed by a processor of the microprocessor.   One example of the program code is the program code disclosed in US Patent 4,896,722 to Upchurch, the disclosure of which is already incorporated herein by reference. In response to the control pulses 18 which have a 'predetermined signature' that are received by the command sensor 14, the microprocessor in the

30   controller board 20 interprets/decodes that 'predetermined signature' (which includes the

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pulse width and/or amplitude and/or rise time of the control pulses 18) and, responsive thereto, the microprocessor in the controller board 20 searches its own memory for a 'particular program code' having a 'particular signature' that corresponds to or matches that 'predetermined signature' of the control pulses 18. When the 'particular signature'

5   stored in the memory of the microprocessor is found, and it corresponds to that 'predetermined signature', the 'particular program code' which corresponds to that 'particular signature' is executed by the processor of the microprocessor. As a result of the execution of the 'particular program code' by the processor, the microprocessor disposed in the controller board 20 energizes the solenoid driver board 22 which, in turn,

10   opens and closes a valve (SV1 and SV2) 12A of the intelligent control valve 12 of figure 15. This operation is adequately described in U.S. Patents 4,796,699; 4,915,168; 4,896,722; and 4,856,595 to Upchurch, the disclosures of which have already been incorporated by reference into this specification.

15   In figure 18, a simple well testing system including an intelligent control valve (ICV) is illustrated. In figure 18, the control pulses 18 of figure 16, having a 'predetermined signature' are transmitted downhole to the intelligent control valve (ICV) 12. In response thereto, a valve 12A associated with the ICV 12 opens and/or closes in a 'predetermined manner' when a microprocessor in the controller board 20 (of figure 17) of the ICV 12

20   executes the 'particular program code' stored therein in the manner discussed above with reference to figures 15, 16, and 17. A wellbore fluid flows within the tubing of the well testing system. After the wellbore fluid flows within the tubing, one or more monitoring sensors 24 begin to sense and monitor the pressure, flowrate, and other data of the wellbore fluid which is flowing within the tubing. The monitoring sensors 24 begin to

25   transmit monitoring data signals 24A uphole.

In figure 18, the 'predetermined signature' of the control pulses 18 can be changed. If the 'predetermined signature' of the control pulses 18 is changed to 'another predetermined signature', and when said 'another predetermined signature' of a new set of control pulses

30   18 is transmitted downhole to the ICV 12, the valve 12A of the ICV 12 will now open

and/or close in 'another predetermined manner' which is different than the previously described 'predetermined manner' associated with the aforementioned 'predetermined signature' of the control pulses 18. Every time the 'predetermined signature' of the control pulses 18 is changed and transmitted downhole, the valve 12A of the ICV 12 can

5   open and/or close in a different 'predetermined manner' and, as a result, the pressure and the flowrate of the wellbore fluid flowing within the tubing of figure 18 will change accordingly and, as a result, the monitoring sensors 24 will sense that changed pressure and flowrate of the wellbore fluid flowing in the tubing and will generate an output signal representative of that changed pressure and flowrate which is transmitted uphole. By way

10   of example, refer to the U.S. Patent 4,896,722 to Upchurch which has already been incorporated by reference into this specification.

In figure 19, the simple well testing system including the intelligent control valve (ICV) 12 of figure 18 is illustrated; however, in figure 19, a computer apparatus 30, adapted to

15   be located at a surface of the wellbore and storing a 'monitoring and control process' program code 30A stored therein, is illustrated. In addition, in figure 19, a simulator, known as the 'Eclipse simulator' 32, adapted for modeling and simulating the characteristics of the oil reservoir layer, is also illustrated. In figure 19, when the monitoring sensors 24 transmit their output signals 24A uphole, representative of the

20   pressure and/or flowrate and/or other data of the wellbore fluid flowing within the tubing of the well testing system of figure 19, those output signals 24A will be received by the computer apparatus 30 which is located at the surface of the wellbore. The computer apparatus 30 stores therein a program code known as the 'monitoring and control process' 30A, in accordance with one aspect of the present invention. The output signals 24A,

25   which are generated by the monitoring sensors 24, will hereinafter be referred to as the 'Actual' signals, such as the 'Actual flowrate' or the 'Actual pressure', etc, since the output signals 24A sense the 'Actual' flowrate and/or the 'Actual' pressure of the wellbore fluid flowing within the tubing of the well testing system of figure 19. When the computer apparatus 30 executes the monitoring and control process 30A in response

30   to the 'Actual' signals 24A, the computer apparatus 30 generates an output signal which

ultimately changes the 'signature' of the intelligent control pulses 18 of figure 19. In the meantime, in figure 19, an 'Eclipse simulator' 32 models and simulates the characteristics of the oil reservoir layer of figure 19, and, as a result, the 'Eclipse simulator' 32 predicts the flowrate and/or the pressure and/or other data associated with the wellbore fluid

5   which is being produced from the perforations 34 in figure 19, as indicated by element numeral 36 in figure 19. The 'Eclipse simulator' can be licensed from, and is otherwise available from, Schlumberger Technology Corporation, doing business through the Schlumberger Information Solutions division, of Houston, Texas. The arrows 38 being generated by the 'Eclipse simulator' 32 of figure 19 represent the flowrate and/or the

10   pressure and/or other data associated with the wellbore fluid which the 'Eclipse simulator' 32 predicts will be produced from the perforations 34 in figure 19. As a result, the arrows 38 being generated by the 'Eclipse simulator' 32 of figure 19 represent 'Target' signals 38, such as a 'Target' flowrate 38 and/or a 'Target' pressure 38 and/or a 'Target' other data 38 associated with the wellbore fluid which the 'Eclipse simulator' 32

15   predicts will be produced from the perforations 34 in figure 19.

In operation, referring to figures 17, 18, and 19, the intelligent control pulses 18, having a 'predetermined signature' are transmitted downhole and the pulses 18 are received by the intelligent control valve (ICV) 12. That 'predetermined signature' of the pulses 18 are

20   received by the command sensor 14 and, ultimately, by the controller board 20. The 'predetermined signature' is located in the memory of the microprocessor in the controller board 20, a 'particular program code' corresponding to that 'predetermined signature' and stored in the memory of the microprocessor is executed, and, as a result, the valve 12A of the ICV 12 is opened and/or closed in a 'predetermined manner' in accordance with the

25   execution of the 'particular program code'. Wellbore fluid, having a flowrate and pressure and other characteristic data, now flows within the tubing of the well testing system of figure 19. The monitoring sensors 24 will now sense the 'Actual' flowrate and/or the 'Actual' pressure and/or other 'Actual' data associated with the wellbore fluid that is flowing inside the tubing of figure 19, and output signals 24A are generated from

30   the sensors 24 representative of that 'Actual' data. Those output signals 24A are

provided as 'input data' to the computer apparatus 30 which can be located at the surface of the wellbore. In the meantime, the 'Eclipse simulator' 32 predicts the 'Target' flowrate and/or the 'Target' pressure and/or the 'Target' other data associated with the wellbore fluid which, it is predicted, will flow from the perforations 34 in figure 19, and

5   output signals 38 are generated from the 'Eclipse simulator' 32 representative of that 'Target' data. Those output signals 38 are also provided as 'input data' to the computer apparatus 30 which can be located at the surface of the wellbore. Now, the computer apparatus 30 receives both: (1) the 'Actual' data 24A from the sensors 24, and (2) the 'Target' data 38 from the simulator 32. The computer apparatus 30 compares the

10   'Actual' data 24 with the 'Target' data 38. If the 'Actual' data 24 does not deviate significantly from the 'Target' data 38, the computer apparatus 30 will not change the 'predetermined signature' of the intelligent control pulses 18. However, assume that the 'Actual' data 24A does, in fact, deviate significantly from the 'Target' data 38. In that case, the computer apparatus 30 will execute the program code that is stored therein

15   which is known as the 'Monitoring and Control Process', in accordance with one aspect of the present invention. When the 'Monitoring and Control Process' is executed by the computer apparatus 30, the 'predetermined signature' of the intelligent control pulses 18 is changed to another, different signature which is hereinafter known as 'another predetermined signature'. A new set of control pulses 18 is now generated which have a

20   'signature' that corresponds to said 'another predetermined signature'. That new set of control pulses 18 are transmitted downhole, and, as a result, the valve 12A of the ICV 12 opens and/or closes in a 'another predetermined manner' which is different than the previously described 'predetermined manner'; for example, the valve 12A may now open and close at a rate which is different than the previous rate of opening and closing. As a

25   result, the wellbore fluid being produced from the perforations 34 will now be flowing through the valve 12A and uphole to the surface at a flowrate and/or pressure which is now different than the previous flowrate and/or pressure of the wellbore fluid flowing uphole. The sensor 24 will sense that flowrate and/or pressure, and new 'Actual' signals 24A will be generated by the sensor 24. Those new 'Actual' signals will be compared, in

30   the computer apparatus 30, with the 'Target' signals from the simulator 32, and, if the

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'Actual signals' are significantly different than the 'Target' signals, the 'Monitoring and control Process' will be executed once again, and, as a result, the signature of the control pulses 18 will be changed again and a third new set of control pulses 18 will be transmitted downhole. The aforementioned process and procedure will be repeated until

5   the 'Actual' signals 24A are not significantly different than the 'Target' signals 38. If the 'Actual' signals 24A remain significantly different than the 'Target' signals 38, the 'Eclipse simulator' 32 will adjust the 'Target' signals 38 to a new value, and the above referenced process will repeat itself once again until the 'Actual' signals 24A are approximately equal to (i.e., are not significantly different than) the 'Target' signals 38.

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In the above discussion, we have been discussing one valve in one well and the pulse to control the one valve in the one well. One of ordinary skill in the art would realize that the above discussion could extend to either multiple valves in a single well or multiple valves in multiple wells. In addition, instead of controlling an Intelligent Control Valve

15   (ICV), one could use the above method in the above discussion to control an active downhole fluid lift method, such as: (1) an Electro-Submersible Pump or ESP, (2) gas lift, (3) a Beam pump, (4) a Progressive Cavity Pump, (5) a Jet Pump, and (6) a downhole separator.

20   A detailed construction of the "monitoring and control process" 30A of figures 18 and 19 in accordance with the present invention is set forth below with reference to figures 1 through 14 of the drawings. A workflow or flowchart of the "monitoring and control process" 30A is illustrated in figures 12, 13, and 14.

25   Referring to figures 1 through 14, the 'monitoring and control' process of the present invention is illustrated. We begin this discussion with a simple example to illustrate the phenomenon, with reference to figures 1 through 11, before explaining the workflow of figures 12, 13, and 14.

Consider the case of a single oil reservoir layer. The reservoir is intersected by a well with an ICV placed in the layer (see reference 1 below). The valve allows the rate of fluid movement between the reservoir and the interior of the well to be changed by changing the valve position. Consider that the well is used to inject water into the oil

5   layer to help push the oil toward another well that is producing the oil from the reservoir layer. Further, suppose that as a result of previous predictions or numerical modeling of the reservoir and well, it has been determined that the ideal way to inject water into the layer is at a low constant rate. At a constant rate, the cumulative or running total of water is a straight line increasing function of time, as illustrated in Figure 1. At the bottom of

10   Figure 1, it is indicated that the downhole choke (ICV) is positioned in the first of 4 possible opening positions. The straight line cumulative trend is called the *target*, since it is the optimum rate and it is desired to maintain the water injection as close as possible to this line.

15   Suppose the reservoir begins production, and during the start-up time, water is injected into the well as planned. Figure 2 illustrates the situation after 2 weeks. The actual cumulative injection is a wiggling line hovering around the target, meaning that the process of injecting water into the layer is proceeding without problem.

20   Figure 3 shows the situation after 4 weeks. Now, perhaps because the source of injected water failed, the rate of injection has dropped to zero and the cumulative injection curve levels of to have zero slope. Now, the actual cumulative injected volume is well below the desired target value.

25   In Figure 4, the result is shown of evaluating what would happen if the downhole choke (ICV) is moved to position 2. The circle shows that opening the valve would move production in the upward direction. It is therefore decided to open the ICV and continue production, as illustrated in Figure 5.

Now, after 10 weeks of injection, the actual cumulative injection has followed the target, but again is drifting below the target value. In Figure 6, as in Figure 4, the situation is evaluated to see what would happen if the ICV were once again opened one position to position 3. This would move the cumulative production in the positive (upward)

5   direction, so this is decided.

Figure 7 shows the result of continuing production with the ICV in position 3 out of 4. Now, unfortunately, the cumulative volume is not increasing near the target. Further, as shown in Figure 8, evaluating what would happen if the valve were opened to the last

10   position number 4, it is seen that the correction is insufficient to return the cumulative injection to the target. Sure enough, as shown in Figure 9, after 15 weeks, the discrepancy between the actual and target curves is unacceptably large.

Figure 10 shows that at this time, it is necessary to re-evaluate the overall behavior of the

15   numerical model of the reservoir, and a new target (starting at week 15) is determined, assuming that the valve stays in position 4.

Figure 11 shows that continuing at the new injection rate, the actual and target curves overlay, and the process is proceeding without problem.

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The simple example just shown illustrates an approach toward adjusting downhole control valves based on frequent (e.g. hour-day) monitoring data such as the downhole pressure or the flow rate into an oil or gas reservoir layer.

25   Figures 12-14 show a series of three workflow diagrams. Figure 12 is the high level summary of the workflow. Figure 12 contains a slow and fast loop, each of the slow loop and the fast loop being shown in greater detail in Figures 13 and 14, respectively.

What follows is a description of these detailed workflows.

Field Optimization Workflow

Fig 12 illustrates a high-level workflow; the individual activites or tasks are numbered
5   and keyed to the text below. This workflow contains slow and fast loops (described in
Appendices 2 and 3 below) that interact at a high level as shown. In the slow loop,
reservoir-network simulation is used to define the optimal future development of the
field. The fast loop translates the results of the slow loop into day-to-day operational
controls of the field, e.g. ICV settings, etc. Overall, the workflow is expected to comprise
10   the following series of modeling and planning activities:

- Slow loop – A coupled reservoir-network model (CRNM) A is used to predict
  optimal future target pressures P_{tk} and target multiphase flow rates F_{tk} B for wells and
  zones at time step k. Fig 1 shows a simple example of an output of this process,
15   specifically, a target zonal injection rate over a period of 17 weeks, computed using a
  simulator. The CRNM also predicts the future network line assignments L_{tk}. Line
  assignments are the matching of individual wells in a group to one of two subsea
  production lines. Then, based on CRNM target information P_{tk} and F_{tk}, a well-
  network model (WNM) is used to predict the optimal future target downhole valve
20   settings S_{tk}. For the initial time step, the CRNM is defined through a characterization
  process based on available reservoir, geologic and well data.
- The valve settings and line assignments S_{tk} and L_{tk} are sent to the field and they
  become the actual settings S_{ak} and L_{ak}, C.
- The field is produced for a period of time (e.g. several days). During this interval,
25   real-time data are measured, e.g. surface and downhole pressures P_{ak}, multiphase fluid
  rates F_{ak}, etc, D. The measured flow rate data are allocated back to wells and zones,
  as appropriate.
- The observed and targeted cumulative multiphase flow rates are compared E. Figures
  2-12 illustrate the comparison of the targeted (straight line) and observed (squiggle

line) cumulative zonal injection rates for the above example. Additionally, the observed and targeted pressures are compared.

- If the discrepancies between the observed and target values are within some specified tolerance, the model is correctly predicting field performance. No corrective action is
5   required and field production continues for another time step F. Fig 2 is an example with no significant discrepancy observed.

- The observed discrepancies may be large. Continuing with the simple example, Fig 3, shows the observed zonal injection rate up to week 4 where the injector rate has dropped to zero during a period of 2 weeks. In the case of a significant discrepancy,
10   the process enters the Fast Production model G.

- The fast loop computes new valve and line assignments to reduce the discrepancies and return the field pressures and rates closer to the targets. Fig 4 illustrates a new target trajectory (small circle) to return the cumulative injected zonal volume to the initial target.

15 - If the fast loop is unable to determine new valve and line assignments that reduce the discrepancies H, or the trends in the discrepancies suggest that the CRNM is no longer valid, the process returns to the slow loop in #1 to develop new predictive targets.

Slow Loop Workflow

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Fig 13 illustrates the slow loop workflow. Overall, the slow loop workflow, carried out only when required, is expected to comprise the following series of modeling and planning activities:

25 - At time step k, update (I) the CRNM by extending the history match period using the available multiphase well and zonal flow rates F_{ak}, and accounting for any network changes since the last model update: S_{ak} and L_{ak}.

- Check that the history match model is valid J, by comparing the actual measured data against the data predicted from the CRNM, e.g. gas-oil ratios, watercuts, pressures,

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etc versus time. If the model is not valid to within a specified tolerance, update the history match model K by modifying the underlying geomodel.

- Once the CRNM is sufficiently history-matched, run CRNM predictive modeling L to determine new optimal trajectories for pressures P_{tk}, multiphase well and zonal rates F_{tk}, etc M. The CRNM captures the reservoir, well, line, and network effects, and computes the optimal line assignments L_{tk}. The CRNM does model the downhole wellbore, but does not explicitly model the downhole flow control valve settings. Because the CRNM time step size is typically much larger than the interval between adjustments to the production system, the CRNM only produces general trends in the pressure drops across the valves needed to obtain the optimal target rates.

- Based on the predicted CRNM results P_{tk} and F_{tk}, run the WNM N to determine the downhole valve settings S_{tk} O that yield differential pressures which most closely match the predicted differential pressures.

Fast Loop Workflow

The fast loop workflow, illustrated in Fig 14, will be carried out on a day-to-week time scale, and is expected to comprise the following series of activities:

- At time step k, history match the WNM P with the actual multiphase well and zonal flow rates F_{ak} and pressures P_{ak}, accounting for the actual line assignments L_{ak} and valve settings S_{ak}. History matching is carried out by tuning the multiphase flow correlations.

- Discrepancies between the actual and predicted rates and pressures are reviewed. Returning to the earlier example, Fig 7 illustrates the predicted and actual zonal injection cumulative volumes, where a large discrepancy has developed between week 8 and week 13 as a result of loss of injection. Note that discrepancies may be due to planned or unplanned outages, and planned outages may be anticipated and production settings optimized proactively. In the case of large discrepancy, it is necessary to restore the pressure and cumulative rate trends back to the optimally predicted trajectories. Changes in target rates F_{tk} are identified to achieve a smooth

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return to the predicted trends. A smooth return may require minor modifications spread over several time steps.

-   Using the history matched WNM from step #1, and the adjusted rates F_{tk} from step #2, compute Q the set of valve settings S_{tk} R for the next time step to attain the rates F_{tk}.

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References

The following references are incorporated by reference into this specification:

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1.   Algeroy, J. *et al.*, "Controlling Reservoirs from Afar", *The Oilfield Review* (1999), **11** (3), pp 18-29.

2.   Baker, A., *et. al.*, "Permanent Monitoring – Looking at Lifetime Reservoir Dynamics", *The Oilfield Review* (1995), **7** (4), pp. 32-46.

15   3.   Beamer, A., *et. al.*, "From Pore to Pipeline, Field-Scale Solutions", *The Oilfield Review* (1998), **10** (2), pp. 2-19.

The invention being thus described, it will be obvious that the same may be varied in many ways. Such variations are not to be regarded as a departure from the spirit and

20   scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.

WE CLAIM:

1. A method for continuously optimizing reservoir well and surface network systems, comprising the steps of:

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(a) transmitting an input stimulus having a predetermined signature downhole into a wellbore and controlling a downhole apparatus adapted to be disposed in said wellbore;

(b) continuously monitoring an actual characteristic of a wellbore fluid flowing in a
10   tubing of said downhole apparatus in response to the transmitting step and generating actual signals representative of said actual characteristic of said wellbore fluid;

(c) predicting a target characteristic of said wellbore fluid flowing in said tubing and generating target signals representative of said target characteristic of said wellbore fluid;
15

(d) comparing said actual signals with said target signals and executing a monitoring and control process when said actual signals are not approximately equal to said target signals;

20   (e) changing the predetermined signature of said input stimulus in response to the executing step thereby generating a second input stimulus having a second predetermined signature; and

(f) repeating steps (a) through (e), using said second input stimulus, and continuously
25   changing the predetermined signature of the input stimulus until said actual signals are approximately equal to said target signals.

2. The method of claim 1, wherein the predicting step (c) comprises the step of:

(c1) generating a second target signal representative of said target characteristic of said

5   wellbore fluid when, after the repeating step (f), said actual signals are not approximately

equal to said target signals.

3. An apparatus adapted for continuously optimizing reservoir well and surface network

systems, comprising:

10

first means for transmitting an input stimulus having a predetermined signature downhole

into a wellbore and controlling a downhole apparatus adapted to be disposed in said

wellbore;

15   second means for continuously monitoring an actual characteristic of a wellbore fluid

flowing in a tubing of said downhole apparatus in response to the transmitting of said first

means and generating actual signals representative of said actual characteristic of said

wellbore fluid;

20   third means for predicting a target characteristic of said wellbore fluid flowing in said

tubing and generating target signals representative of said target characteristic of said

wellbore fluid;

fourth means for comparing said actual signals with said target signals and executing a

25   monitoring and control process when said actual signals are not approximately equal to

said target signals, said fourth means changing the predetermined signature of said input

stimulus when the execution of said monitoring and control process is complete and

generating a second input stimulus having a second predetermined signature,

said first means for transmitting said second input stimulus having said second predetermined signature downhole into a wellbore and controlling said downhole apparatus,

5   said second means continuously monitoring said actual characteristic of said wellbore fluid flowing in a tubing and generating further actual signals representative of said actual characteristic of said wellbore fluid,

said third means generating said target signals representative of said target characteristic

10   of said wellbore fluid, and

said fourth means comparing said further actual signals with said target signals and continuously re-executing said monitoring and control process until said actual signals are approximately equal to said target signals.

15

4. The apparatus of claim 3, wherein said third means generates further target signals representative of said target characteristic of said wellbore fluid when said actual signals are not approximately equal to said target signals, said fourth means comparing said further actual signals with said further target signals and continuously re-executing said

20   monitoring and control process until said further actual signals are approximately equal to said further target signals.
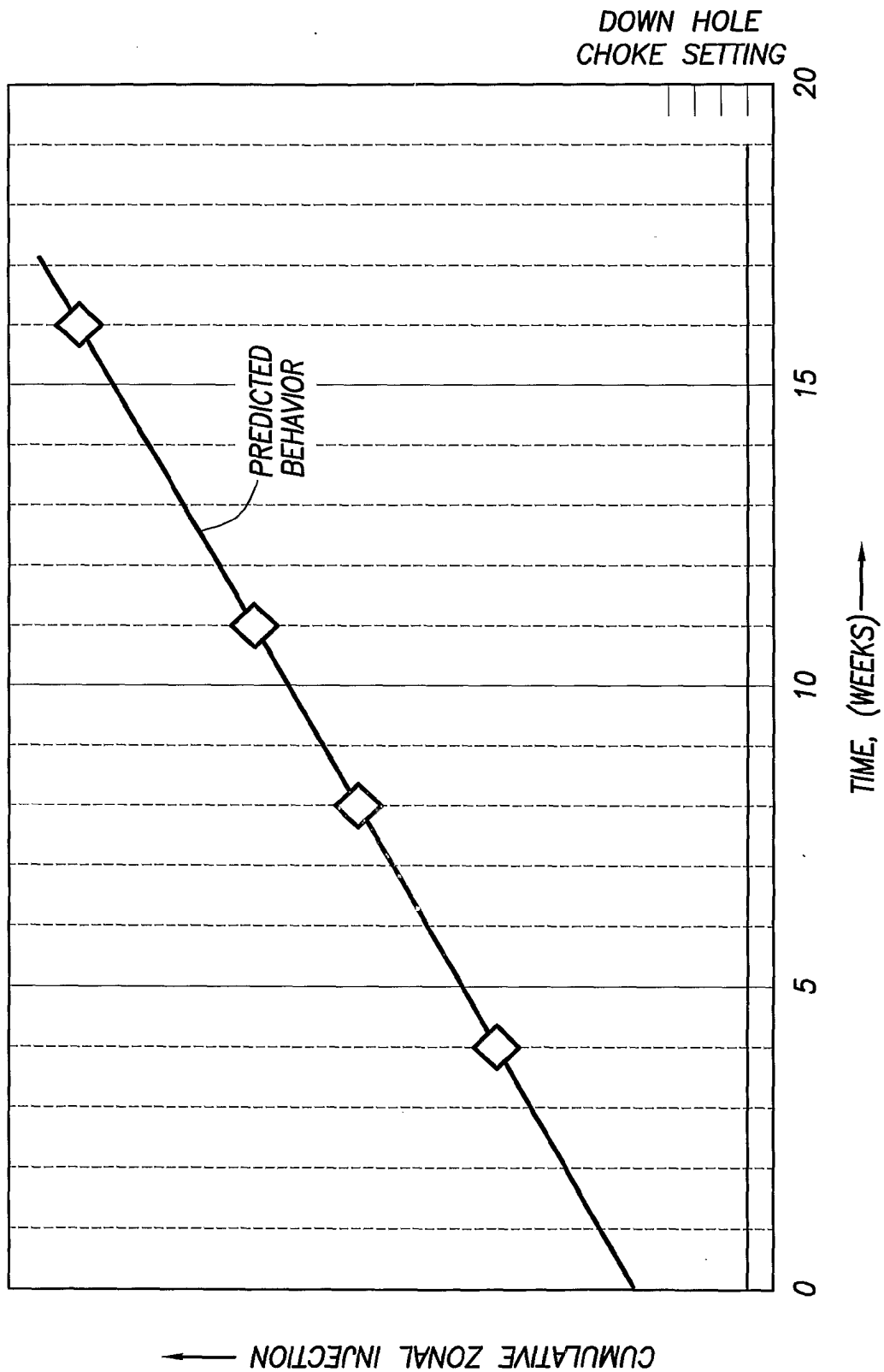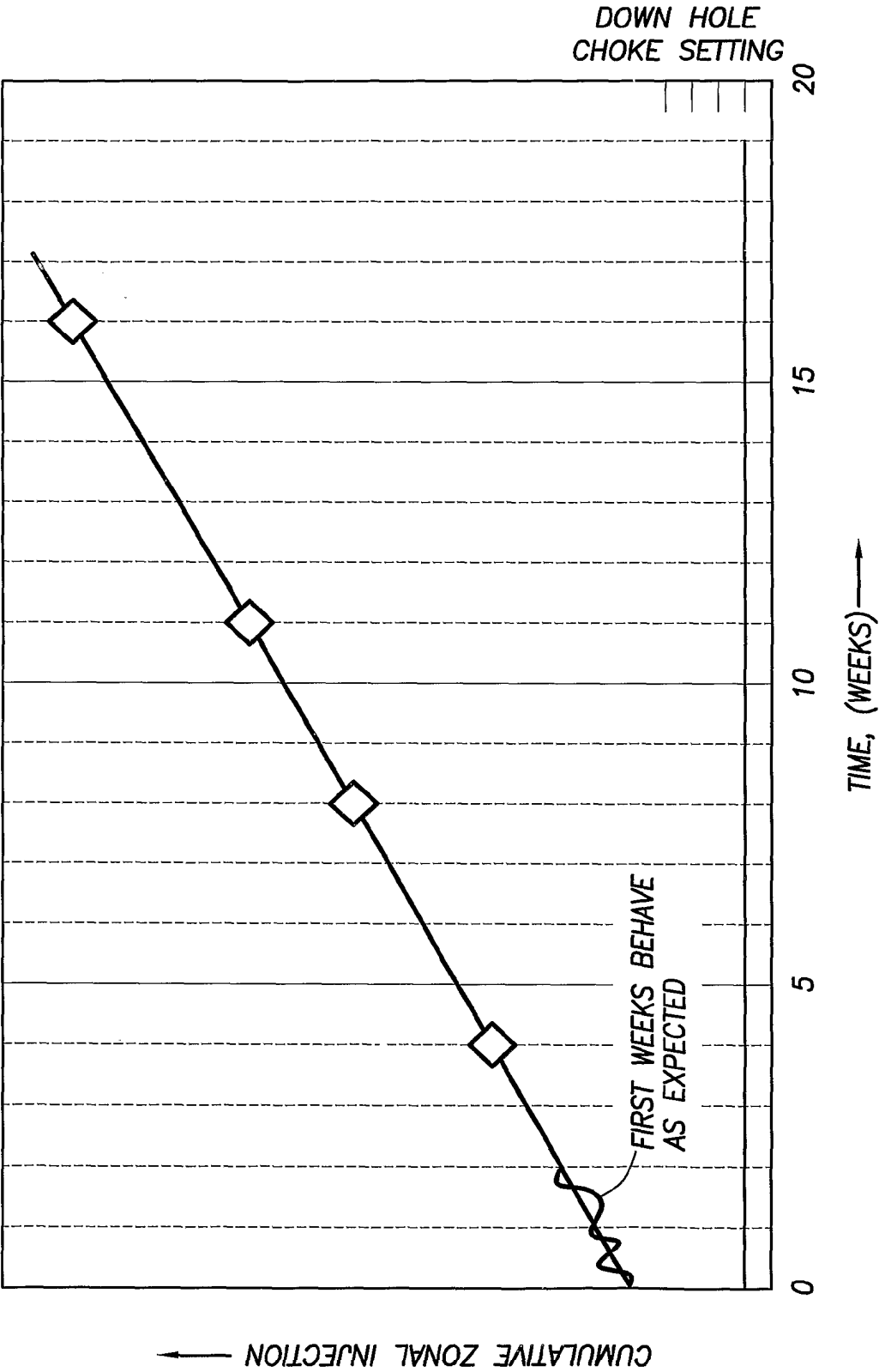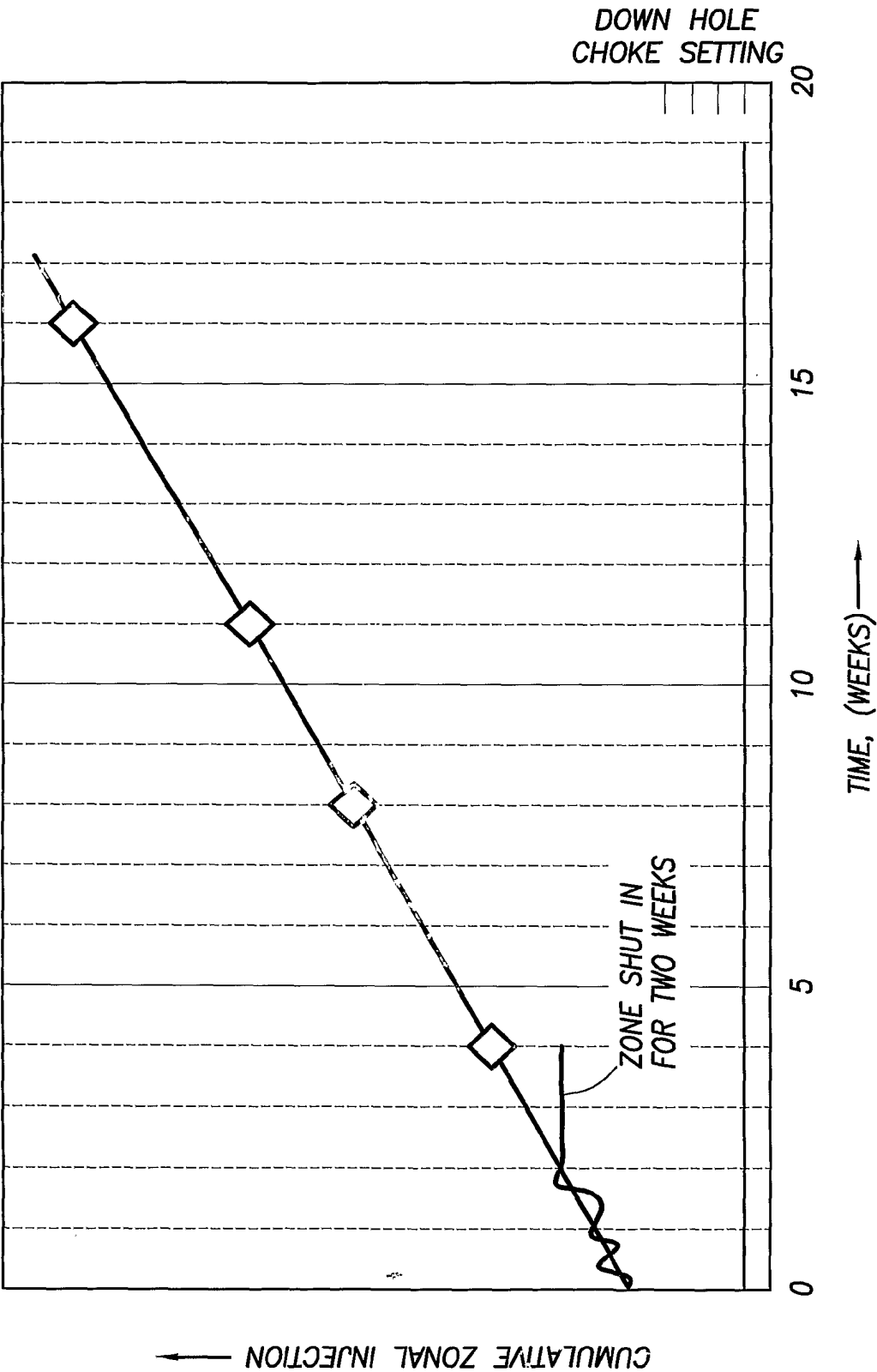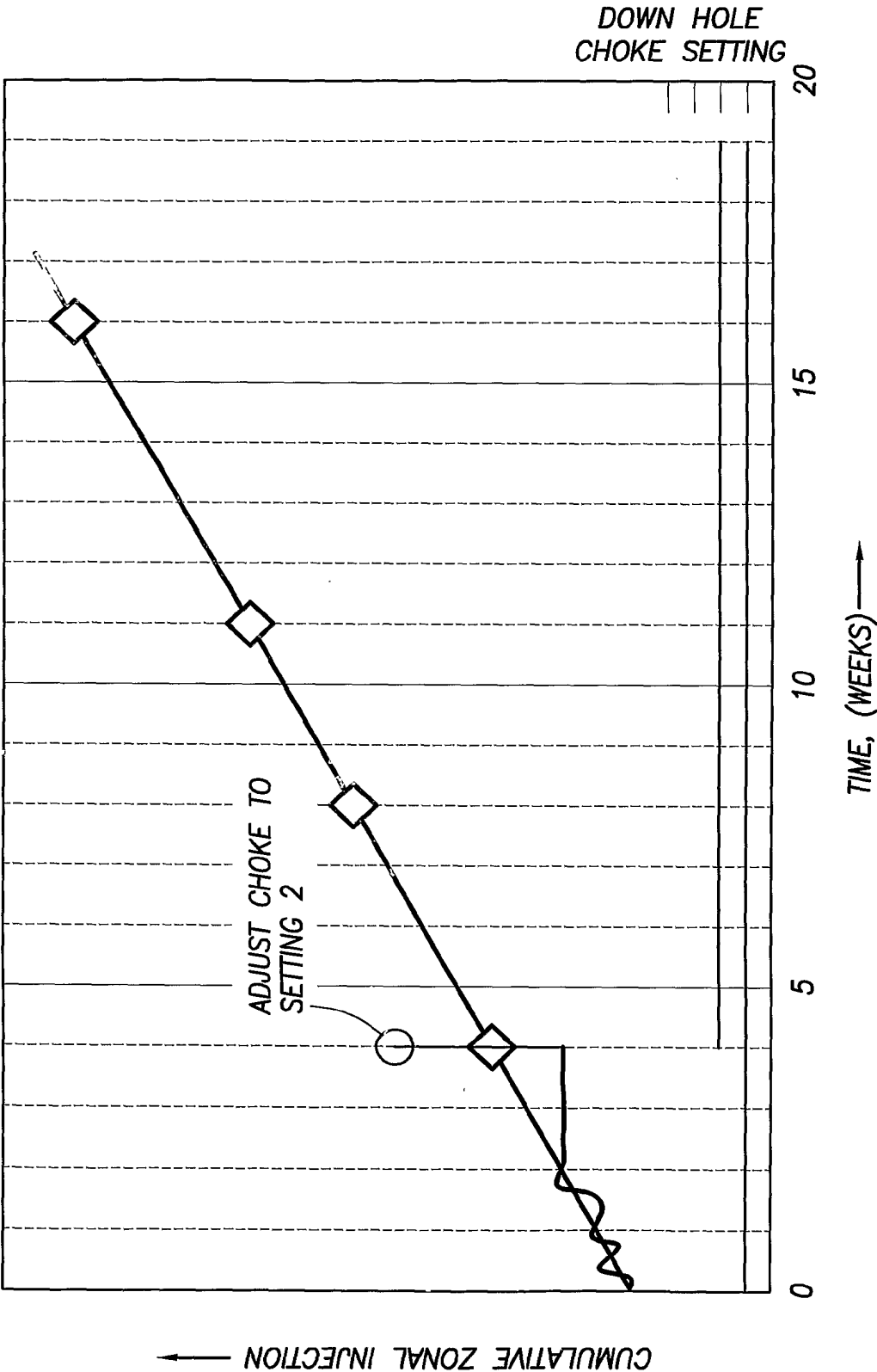
FIG.1

FIG.2

FIG.3

FIG.4

5/17

FIG.5

FIG.6

FIG.7

FIG.8

FIG.9

FIG.10

FIG.11

FIG.12

FIG.13

14/17

FIG.16

18

T-1   T-2

<500 PSI

P-1

P-2

PRESSURE

TIME

INSURE FIDELITY OF WNM MODEL

ADJUST CHOKE SETTINGS TO CHANGE TRAJECTORY TO GET BACK ON TRACK

HM WNM

P

WNM

Q

NEW VALVE SETTINGS Stk

R

FAST PRODUCTION MODEL

FIG.14

15/17

FIG.15

FIG.17

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                                            20              22
                                             ⌐              ⌐
  ┌──────────┐   ┌──────────┐   ┌──────────┐   ┌──────────┐      ┌────────┐
  │ COMMAND  │→  │ COMMAND  │→  │CONTROLLER│→  │ SOLENOID │─────→│  SV 1  │
  │  SENSOR  │   │ RECEIVER │   │  BOARD   │   │  DRIVER  │      └────────┘
  │          │   │  BOARD   │   │          │   │  BOARD   │      ┌────────┐
  └──────────┘   └──────────┘   └──────────┘   └──────────┘─────→│  SV 2  │
                                                                 └────────┘
       14            16
                           ┌──────────┐   ┌──────────┐
                           │  POWER   │   │          │
                           │  SUPPLY  │←──│ BATTERY  │
                           │  BOARD   │   │          │
                           └──────────┘   └──────────┘
```

12

12A

INTELLIGENT CONTROL PULSES

18

OIL RESERVOIR
LAYER

24A

OIL RESERVOIR
LAYER

24

12

ICV

12A

MONITORING SENSORS
FOR MONITORING
PRESSURE AND
OTHER DATA AND
SENDING MONITORING
DATA SIGNAL UPHOLE

INTELLIGENT CONTROL
VALVE (ICV) TO BE
OPENED AND CLOSED

FIG.18

ADJUST THE INTELLIGENT
CONTROL PULSES IN ACCORDANCE
WITH MONITORING AND CONTROL
PROCESSES

18

'ACTUAL' FLOW

INTELLIGENT CONTROL PULSES

24A

OIL RESERVOIR
LAYER

OIL RESERVOIR
LAYER

32

SENSOR WILL
SENSE AN 'ACTUAL'
FLOW OF WELLBORE
FLUID IN TUBING

ECLIPSE SIMULATOR
PREDICTS A
PARTICULAR 'TARGET'
FLOW OF
WELLBORE FLUID

34   38

24

36

38

24A

ICV——12

'TARGET'
FLOW

'ACTUAL'
FLOW

COMPUTER APPARATUS

MONITORING AND CONTROL PROCESS

30A

30

FIG.19

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US02/03224

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) :E21B 43/00, 43/12
US CL : 166/250.01, 250.15, 369, 373, 53, 66.6
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
U.S. : 166/250.01, 250.15, 369, 373, 53, 66.6, 65.1, 66

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EAST

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,633,954 A (DIXON et al.) 06 January 1987, see entire document.	1-4
A	US 5,597,042 A (TUBEL et al.) 28 January 1997, see entire document.	1-4
A	US 5,732,776 A (TUBEL et al.) 31 MARCH 1998, see entire document.	1-4
A	US 5,975,204 A (TUBEL et al.) 02 November 1999, see entire document.	1-4
A	US 6,046,685 A (TUBEL) 04 April 2000, see entire document.	1-4

☐ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
"E"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
02 MAY 2002	28 MAY 2002

Name and mailing address of the ISA/US	Authorized officer
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Form PCT/ISA/210 (second sheet) (July 1998)★